A Rapidly Re-deployable Wireless Sensor Network for Structural Assessment by Non-expert End Users: The CITI-SENSE Concept

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Abstract

Most infrastructure managers lack an economically feasible framework for widespread evaluation and prioritization of maintenance efforts for aging infrastructure. Instead largely visual, subjective and infrequent assessment remains the norm, and while structural health monitoring researchers have been able to bring quantitative, autonomous and continuous assessment into practice, it is generally only for signature structures, neglecting the larger population of at-risk infrastructure. Recognizing the expansive inventory that must be assessed and the limited budgets to do so, this paper takes a new approach by introducing CITI-SENSE: a citizen-centric health monitoring paradigm, which represents an entirely new philosophy where every aspect of the hardware, networking and algorithms are designed with citizen end users and their constraints in mind. This paper will introduce the various aspects of the CITI-SENSE effort, such as the hardware design of an autonomous, power-efficient, self-aware multi-metric wireless sensor module packaged for rapid, repeated, re-deployment by non-expert end users. This is made possible through the development of a self-organizing, multi-scale wireless sensor network with autonomous localization aimed at delivering reliable communications with plug-and-play ease. This study will also overview the damage assessment algorithm embedded in the hardware, capable of integrating various sensor measurements to execute decentralized damage detection to enable assessments without a priori knowledge of sensor placement and through the use of a restricted input network activation scheme that seeks to use operational loading while still permitting a reduction in the size of the requisite reference pool of undamaged states. A unique feature of this activation scheme is the engagement of citizens as partners in this process. It is hoped that through the prototype introduced in this study and the removal of previous technological barriers, non-expert end users can truly become stewards of the infrastructure they rely upon to maximize the impacts and prevalence of structural health monitoring in our society.

Introduction

Civil Infrastructure is second only to health care in annual expenditures in the US. And while the health care industry benefits from substantial corporate-sponsored research and development, much directed to the advancement of state-of-the-art diagnostics that can be readily employed by the end users they serve, the same sadly cannot be said for Civil Infrastructure. As a result, this vast network that serves as the lifeline for commerce is crumbling, and our present inability to autonomously detect damage in its early stages implies that corrective measures on key elements like bridges are often not taken until the damage is severe enough to be visually detected, leading to unnecessary cost and commuter inconvenience. In fact, it is estimated that these deficiencies are so severe that their rectification will require $17 billion per year, though only $10.5 billion per year is currently budgeted to do so (ASCE, 2009). With such inadequate resources in hand, and a mounting inventory of troubled bridges, ASCE and others have
recently called for a new inspection paradigm and the implementation of a risk-based prioritization plan for these maintenance efforts (ASCE, 2009).

To achieve this goal, it is essential to remove barriers that have precluded the use of advanced technologies for bridge assessment. In this project, this is achieved in two ways. The first targets those directly charged with infrastructure assessment and management, who, by the removal of technological barriers, will have direct access to sensor networks that autonomously deliver the quantitative assessments and network-level decision support they desire. This aspect is critical. Past and present applications of sensor networks or structural health monitoring (SHM) have been overseen often by researchers who have sole access to, control over and operation of these technologies, alienating the end users the technology is ultimately intended to serve. As a result, it is no surprise that these intangible technologies have not been embraced by the civil engineering community. Therefore this study introduces the concept of CITI-SENSE: a citizen-centric health monitoring paradigm as an entirely new philosophy where every aspect of the hardware, networking and algorithms are designed with citizen end users and their constraints in mind. By design, CITI-SENSE opens the possibility for SHM to wide inventories of bridges through rapidly re-deployable power-efficient sensors in a self-organizing wireless network that will enable end users with no background in electronics or data processing to deploy and operate their own sensor networks on any bridge they desire for as long as they desire. Thus these end users will have the quantitative decision support they need to manage their large inventories of bridges within their limited budgets. More importantly, it will allow them to remove humans from time- and labor-intensive visual inspections into more appropriate venues of response.

The second mechanism for citizen engagement involves their participation in the assessment process itself, as true stewards of the infrastructure they rely upon every day. SHM is only truly cost effective if it is capable of detecting damage in its earliest stages where proactive maintenance can introduce considerable savings. Generally the detection of damage in such early stages with any considerable accuracy requires knowledge of the loading conditions that is not available in most ambient monitoring efforts. Therefore, the CITI-SENSE concept asks commuters and specifically commercial truckers who provide the excitation to instrumented bridges to self-report their payloads. Then when a participating commuter approaches the bridge, an RFID tag is scanned and the network is activated in what is termed a restricted input network activation scheme that would then know the velocity and weight of the passing vehicle at each moment that it traverses the bridge. This ability to essentially control the conditions under which measurements are made without the need for traffic restriction or forced vibration testing represents a significant advantage that can enhance the accuracy of damage detection and reduce the requisite size of the reference pool of undamaged states. Certainly, such a shift in citizen engagement requires the development of incentives and policies that bring the very users of the infrastructure voluntarily into the assessment process; this certainly constitutes a transformative shift in the attitudes related to the stewardship of our public infrastructure that can be achieved in this prototype by waiving fees on tolled highway segments. By successfully achieving such voluntary participation, this study offers citizens themselves an increased role in the assessment and maintenance of the infrastructure they rely upon and fund through their tax dollars – this enables citizens to become proactive participants, as well as the ultimate benefactors of a more reliable infrastructure system.

While the citizen engagement aspects of this project are particularly novel, they in and of themselves are not sufficient to truly address the infrastructure challenges facing many mature nations. But when flanked by many of the other technical innovations at the heart of the CITI-SENSE concept, they can enable damage to be detected sooner than the current biennial inspections would permit, enhancing public safety while facilitating more pro-active maintenance efforts that will be more cost effective and less intrusive to commuters. The subsequent sections of this paper will detail the various levels of citizen engagement at the heart of the CITI-SENSE paradigm.
Level 1 Citizen Engagement: Making SHM Technologies Accessible

By recognizing that the target end users have limited budgets and large portfolios of bridges, it is ridiculous to expect that even a low cost sensor network could or should be permanently installed on the hundreds of thousands of bridges in the United States or any country for that matter. Thus CITI-SENSE operates within this reality to deliver a rapidly re-deployable, self-organizing wireless sensor network that can accurately estimate damage without disrupting the normal operation of the bridge. It is important to note that the use of embedded sensors to evaluate critical infrastructure is a complex task that faces a number of legitimate challenges that are compounded by CITI-SENSE’s end goal of delivering an autonomous system to its end users. And thus, the CITI-SENSE concept can be born only by delivering novel solutions in these four domains and integrating them effectively:

- **Damage Assessment**: multi-metric damage detection operating without knowledge of sensor placement and using innovative schemes for activating the network under only specified loading conditions
- **Hardware**: rugged, power-efficient, self-aware multi-metric wireless sensor module packaged for rapid, repeated, re-deployment by end users
- **Networking**: self-organizing, efficient wireless sensor network with autonomous localization for reliable communications with plug-and-play ease
- **Risk Assessment**: continuously updated, integrated decision-making framework that incorporates feedback from embedded sensors for dynamic risk assessment using user-defined performance criteria to prioritize maintenance efforts.

It should be noted that although an innovative risk assessment platform that integrates the quantitative information garnered from structural monitoring is essential and a major component of the CITI-SENSE effort, for brevity, this will not be the focus of the following sections.

### Damage Assessment

There have been considerable efforts in damage detection in structural engineering, though most remain grounded in largely academic problems (Doebling *et al.*, 1998; Farrar and Doebling, 1997; Doebling *et al.*, 1996), and thus the ability to use the output of embedded sensors to detect damage in actual structures has been largely unsuccessful (Kijewski-Correa *et al.*, 1998). The reasons for this are not trivial, and this barrier in particular has been and will continue to be the most critical to overcome to build public trust in SHM. In our opinion, there are three causes for these failures, to which we now present our solutions:

1. **Multi-Metric Sensing**: Damage is inherently a local phenomenon and thus the expectation that it can be completely characterized, particularly in its earliest stages, by a single global response quantity like acceleration, is not realistic. Yet this has been the primary approach used in most previous attempts. For this reason, the CITI-SENSE platform employs multi-metric sensing, previously demonstrated by our team to enhance accuracy of damage detection in wireless platforms.

2. **Unknown Loading Conditions**: Some of the most accurate assessments of infrastructure using embedded sensors have required the controlled excitation of a bridge using large vehicles with known loads. This poses a very intrusive form of testing that requires short-term closure of the bridge and is infeasible for long-term, continuous evaluations. Thus many applications have resorted to the use of ambient vibrations, allowing the natural loadings of vehicles, wind, etc. to be the excitation source. Doing so significantly complicates the assessment process as minor levels of damage must somehow be distinguished from other signal anomalies associated with variations in environmental and vehicular loading patterns. While some have attempted to make this distinction using extensive reference pools of data for the bridge in its undamaged condition,
it is unreasonable to expect that those pools could realistically encompass all the possible loading conditions a bridge may experience in the future. Thus, if a future measurement is generated under loading and/or environmental conditions not encompassed by that reference database, they may be erroneously identified as damage, even though the structure is perfectly healthy. These false positives can severely erode public confidence in the technology. To overcome this challenge, CITI-SENSE offers a compromise between these two extremes, with a novel element of citizen engagement: instead of attempting to control the loading on the bridge, we allow the bridge to be naturally excited, but perform assessments only when those natural excitations match target conditions used in the development of the reference database. To create a truly citizen-enabled approach, these natural excitations are provided by trucks marked with RFID tags that enable the arrival of a vehicle with known payload to be identified and tracked as it moves along bridge, while the sensor network records the responses under this known loading condition. By doing so, this effort offers the users of civil infrastructure a vital role in its assessment and maintenance and brings a particularly novel means to quantify these loading conditions.

3) **Decentralized Damage Assessment:** In order to deliver technology that can be re-deployed with sufficient flexibility for a large inventory of bridges, the assessment framework cannot rely on any model-based approaches, including the use of finite-elements or structural stiffness/flexibility matrices, as these require explicit knowledge of the degrees of freedom being monitored and even data exchange between those degrees of freedom (Doebbling et al., 1998; Farrar and Doebbling, 1997). With this requirement in place, the vast majority of damage detection algorithms in the literature would be precluded from CITI-SENSE, requiring the use of identification approaches that can operate in a decentralized manner to detect damage only from the vibration signals recorded and processed locally. Further, when using model-based approaches that require data streams from tens or even hundreds of sensors in order to make a damage decision, synchronization and loss intolerance become issues. However, by localizing all processing at the sensor node, these issues are avoided and the overall lifetime of the wireless sensors are extended since only select parameters are transmitted through the network. To achieve this, CITI-SENSE utilizes time series regressive modeling of multi-metric sensor outputs and a data-driven damage sensitive feature to offer truly flexible, decentralized approach.

The damage detection approach adopted herein to achieve the three aforementioned goals is based on time-series regressive modeling. In fact, the introduction of such a two-stage approach by Sohn et al. (2000) even enabled changes in the environmental and operational conditions of the system to be distinguished from actual damage. However to do so, the approach required a massive database of measurements conducted on the bridge in its undamaged condition encompassing all possible loading scenarios, which is not practical. However, these limitations are addressed by again employing regressive models, but incorporating multiple sensing elements and a computationally efficient, data-driven damage sensitive feature (DSF) verified against a comparatively smaller reference pool. The rationale for such a multi-metric approach is detailed in Kijewski-Corra et al. (2006a), Su and Kijewski-Corra (2007), and Su et al. (2009). These efforts have affirmed that damage, as an inherently local phenomenon, can be best detected considering both acceleration and strain responses.

Considering again the blind deployment constraint, any DSF based on the coefficients of this model must be sufficiently adaptive given that the citizen end-users will have the liberty to select the placement, while still being embeddable in the wireless platform. Thus a uniquely data-driven DSF was proposed by Su and Kijewski-Corra (2007) and will be employed herein. The premise for this DSF is slightly different than its predecessors (Nair et al., 2006) in that it is completely data-driven and directly incorporates information from the reference pool of undamaged states (mean and standard deviation). Extensive validations (Kijewski-Corra et al., 2006a; Su and Kijewski-Corra, 2007; Su et al., 2009,
Kijewski-Correa and Su, 2009) have verified the superior performance of this DSF in not only signaling damage but also in localizing that damage and assessing its severity (Su et al., 2009).

Despite the advances that have been made in data-driven damage detection from diverse sensing elements, there remains the need to distinguish variations in DSF values due to operational and environmental fluctuations from actual damage within the system. By conceding that the input excitations to the bridge cannot be known explicitly or controlled in any kind of in-service assessment, the damage detection algorithms must include a specific mechanism for treating these unknown inputs, which in the past has required an exhaustive reference database. The DSF employed herein offers particular innovation in that only the statistics of the reference database need to be stored and manipulated locally. However, the generation of an exhaustive reference pool to generate these statistics is still impractical. Thus, CITI-SENSE offers its next supporting innovation.

Kijewski-Correa et al. (2006b) initially proposed a restricted input network activation scheme (RINAS) that would acquire response data only when a target loading condition is satisfied. This in itself was particularly novel compared to competing approaches. Although not being able to control or measure the input, this scheme allowed operational and environmental states to be restricted to a specific subset for which a reliable reference pool had been generated, e.g., the passage of a semi-trailer at night. Since RINAS detected vehicles using imaging techniques, the weight of the vehicle was not known and thus although the input conditions were considerably narrowed, a significant training period was still required to generate the reference database encompassing the many possible payloads trucks of that size could carry. Considering the blind deployment constraint within CITI-SENSE and the provision for rapid deployment and assessment, such a training period could not be supported and thus specific knowledge of the loading condition and its arrival at each sensor location would be necessary to distinguish operational variabilities from actual damage. As a result, CITI-SENSE will utilize self-reported payloads of passing vehicles with RFID tags. This will be detailed further in the section on Level 2 citizen engagement.

Hardware

The concept of wireless sensing is growing in maturity and the ability for rapid deployment and re-deployment of sensors has certainly been enabled by removing one of the most costly and time-consuming installation components: cabling. A number of groups have developed and further advanced wireless sensor hardware over the last decade (e.g., Straser, 1998; Lynch, 2003; Wang et al., 2005), some based on the MICA2 platform developed at Berkeley (Hill, 2000). Researchers have continued to reduce the cost and size of wireless systems (Aoki, 2003), even by partnering with new commercial entities, e.g., Intel’s Imote2 (Nagayama et al., 2005). Some of these technologies have even been demonstrated in short-term field deployments on US bridges (Straser, 1998; Maser, 1996), including San Francisco’s Golden Gate Bridge (Pakzad et al., 2008). However, it can be argued that these and all other past developments shared one common trait: they were largely university research efforts that merely demonstrated that wireless platforms could be used to communicate with a sensing element. As a result little effort was done to create a hardware platform that would be able to withstand the rigors of a long-term deployment with constrained energy and computational resources. Moreover, preliminary deployments did not take into account the need for a reliable, adaptive wireless communication system that would allow the sensor network to operate in an autonomous and energy efficient manner. Thus, in order to deliver a citizen-centric approach to infrastructure assessment, ruggedized hardware has been developed and packaged to enable deployment with “plug and play” ease and the ability to accommodate a suite of different sensing elements. These intelligent wireless systems with reconfigurable radios and energy scavenging electronics enable end users, even those without experience with electronics, to rapidly re-deploy the units on different bridges throughout an inventory.

Wireless Sensor Node: The wireless sensor node developed by EmNet LLC addresses a number of real-life issues that are found in existing embedded network nodes such as Crossbow’s MICA2 processor
module and has already been applied to a number of civil engineering problems (Kijewski-Correa et al., 2009). These issues concerned the limited radio range of the MICA2 module and the need for specialized sensor and wireless interfaces required in this application. The process begins by reducing the form of existing platforms and enabling reliable low-power operation in a compact form (Figure 1). In order to be commercially and technically viable, CITI-SENSE must be able to operate for extended periods of time without intervention and therefore employ mechanisms (efficient battery chargers, solar panels, piezoelectric materials, and highly efficient rechargeable batteries) to extend the battery life of the system beyond 3 years (e.g., Figure 1). Additionally, these devices have the provision to scavenge power directly from the inertial sensors used to measure bridge vibrations by accumulating solar or vibration energy in a large capacitor. A “nano-powered” voltage comparator then determines when the energy stored in the capacitor reaches a certain value to activate a pump-up switching power supply that pushes the charge into a rechargeable battery.

While energy-scavenging techniques have previously been shown to be feasible, concurrent reliable low-power communication has been the Achilles’ heel of wireless sensor networks. Several approaches to the realization of mesh network communication protocols (Akyildiz, 2002; Heinzelman, 1999, 2000; Intanagonwiwat, 2000; Manjeshwar and Agarwal, 2002) typically assume a dense node population and good internodal connectivity. CITI-SENSE radically differs from this paradigm. Nodes in CITI-SENSE are sparse and have poor internodal reception mainly due to the presence of large concrete or metallic obstacles and their ad-hoc distribution by non-expert end users. Therefore, Stateless Gradient-Based Persistent Routing is employed due to its low computational requirements and robustness. This approach routes from the source to the destination based on a gradient structure imposed on the network (Maróti, 2004; Braginsky, 2002). Each node in the network has a gradient number that is an indication of how close the node is to the network’s central gateway node. When a node in the network desires to transmit a data message to a gateway it will use its gradient information to route the data packets and navigate through the network. Since there is no explicit routing information generated, there is minimum computational complexity in this protocol as opposed to traditional Bellman-Ford or Dijkstra-based approaches (Perkins, 1999; Johnson and Maltz, 1996). Moreover, the network is inherently more resilient to node failure.

To further enhance power conservation in the hardware, a new optimized middleware stack is implemented that shortens the active part of the duty cycle, preserving the throughput of the network by (a) implementing a tighter synchronization algorithm based on the FHSS (Frequency Hopping Spread Spectrum) synchronization signal generated in both receiver and transmitter radios, (b) adaptively adjusting the retransmission of packets based on the forwarding acknowledgements received and link
probability of successful transmission, (c) implementing a tighter medium access layer that uses a new MAC (Medium Access Control) implemented by the radio manufacturer that introduces random delays before transmission, (d) imposing constraints on the forwarding gradient conditions to enforce more optimal route generation thus reducing the number of retransmissions, (e) eliminating excessive retransmissions by assigning IDs to the messages, and (f) forwarding messages to known reliable neighbors. This allows the routing algorithm to scale better and adapt to the infinite number of unknown network configurations the non-expert end user may ultimately specify, at the cost of a slight increment in computational complexity.

However, in order to further maximize sensor network performance under an arbitrary deployment, sensor nodes must be adaptable to their surrounding environment. This is achieved by making self-aware system that can sense the surrounding electrical environment and dynamically change the antenna configuration and/or impedance. In a common cell phone-type wireless application, the near field environment is usually not accounted for since cell phones are able to use an inefficient electrically small antenna and are expected to be recharged every day or so. In contrast, the deployed sensor network does not have the recharging luxury. The difference in efficiency will directly tie into the service lifetime of each of the sensor nodes. In most medium range sensor applications, including the bridge network monitoring, the transmit power represents the largest source of power drain for the node. Typically wireless nodes will employ a single whip antenna, which is required to be a certain distance above a ground plane to get optimal performance. This severely limits the ways in which a sensor network can be deployed. When a node is placed at one of the worst possible locations—surrounded by conductive metallic objects—and when additional RF inefficiencies are introduced (sub-optimal antenna pointing in the wrong direction), wireless links that would normally be continuously error-free will become highly unreliable. Therefore, adding an adjustable antenna configuration end to the nodes was necessary to transform its impedance to a non-lossy value and to select among multiple antennas in the vicinity of the metallic structures. In total, the wireless node developed for CITI-SENSE will have an innovative low-power design, will be capable of supporting multiple sensing elements, will possess self-awareness to adapt to potentially unfavorable transmission environments, and the ability to self-organize when deployed in an unknown configuration.

Low-Power Integrated Inertial Sensor: Despite all the power conserving measures in the wireless hardware, communications protocols, restricted network activation and decentralized processing of data, high precision sensing elements continue to have high power demands and are generally not capable of being duty cycled as proposed. While high-output piezoelectric accelerometers can have power consumption several orders of magnitude lower than force-balance accelerometers, piezoelectric accelerometers have however poor response at low frequencies and are subject to thermal transients that are common in large bridge structures. Force-balance accelerometers offer the advantage of being able to measure accelerations with frequency components down to 0 Hz; however, they consume substantial amounts of power. As such, this study is developing two new sensing elements: a highly efficient force-balance accelerometer more suitable for wireless platforms that minimizes power consumption without jeopardizing performance; and a magnetic velocity sensor technology, not previously applied in civil infrastructure. As discussed previously, an added feature of this hardware design is the ability to harvest energy from the devices when the wireless network is not actively acquiring data.

Networking

When considering the need for a citizen-centric approach that would enable end users themselves to deploy hardware repeatedly on different bridges, surrendering knowledge of the exact locations where they will be placed, it becomes clear that these wireless networks will need to have capabilities beyond the typical platform. In general, wireless communication faces unique challenges surrounding power management, transmission reliability and scalability that have prompted a trend toward multi-scale or tiered network concepts (Mitchell, 2000; Kottapalli 2003); however, our network concept adds a level of
complexity by requiring self-organization through electronic tagging and a localization scheme using an unsupervised exchange of messages. To our knowledge, every past and present application of sensing to assess infrastructure requires full knowledge of where sensors are placed for not only the damage detection algorithm but also to achieve desired communications throughput. As CITI-SENSE aims to bring technology to the people, it places the burden for network organization and operation on the network itself so that end users can place and relocate the hardware at will.

**Deployment and Localization:** While the aforementioned wireless platform and the new integrated inertial sensor provide the required low-power, multi-metric sensing element, the more substantial novelty in the hardware is their capability for self-organization. In order to create a generalized, flexible system that places assessment technologies in the hands of citizen end-users, so to take advantage of and benefit from the experience developed over years of bridge inspections, all aspects of the assessments and communications within the network cannot assume a priori knowledge of their location on the structure. Specific to the wireless network and its supporting hardware, this requires autonomous localization capabilities so the exact locations of sensors and the potential defects they may detect can be reported.

Sensor localization has received significant attention since the early days of sensor networks (Zhao and Guibas, 2004; Bulusu and Jha, 2005; Karalar and Rabaey, 2006; Römer, 2005). These approaches have largely relied on sound waves and microphones, which are likely not viable in the present application due to traffic noise and structural interferences. Radio frequency waves have been much more popular in sensor localization applications, and while GPS may be a possibility, some if not all of the actual sensor locations will be in GPS-denied locations. In fact, the likely placements of these sensors will create significant obstacles for any type of RF wave transmission.

These challenges are overcome by electronic marking at the time of placement (transmittal of focused beam at local antennas set up at the corners of the bridge), followed by an automatic unsupervised exchange of messages and the use of established localization algorithms (He et al., 2003; Kusy et al., 2006) to extract their exact positions. The localization antennas, with adaptive directionality and impedance matching to increase reception capabilities, can be used not only for the localization and but also to assist the gateway station in collecting data. The positions of these antennas are fixed by on-board global GPS referenced to the gateway station. Thus the deployment process would initiate with the placement of a gateway station up traffic of a candidate bridge. The gateway station would include an RFID scanner and meteorological station necessary for the restricted network activation, a GPS antenna/receiver, a wireless platform to communicate with sensor array, and cellular card to communicate with the off-site database. The gateway would be powered by solar panels or dedicated power, if available on site. The downward-directed localization antennas would be positioned at the four corners of the bridge and their GPS cards would identify their position referenced to the gateway station. The wireless sensor nodes can then be arbitrarily deployed on the bridge, electronically marked as they are placed and then the network would be activated by a user interface to complete the localization and then begin acquiring data in its normal operating mode. The overall concept of the deployment and localization stages through the assessment stage is shown in Figure 2, emphasizing that once in assessment mode, any indication of damage, its location and severity, is relayed in near real time to the relevant officials by email or text message. After this stage of alerting, the information is relayed into the decision making framework to determine the appropriate next steps.
Level 2 Citizen Engagement: Citizens as Active Participants in SHM

As mentioned previously, in order to achieve a manageable reference pool of undamaged states, the input conditions under which responses are monitored must be sufficiently restricted. It was previously
proposed to do so in a more qualitative sense by using camera based technologies to identify the arrival of large semi-trailers. However, such a visual triggering mechanism does not provide any information on the load this vehicle would impart on the bridge. Therefore, CITI-SENSE introduces a particularly novel approach. RFID technologies are incorporated in this project as an economically and technically feasible way of identifying and selecting target loads that will be used to assess the structure’s health, using an innovative engagement of citizen commuters. Given the requirement that input loads must sufficiently excite the instrumented bridge and must do so in a way that is distinguishable enough to form the basis for restricted activation, the targeted vehicles for restricted input activation will be trucks towing loaded semi-trailers. The information necessary for assessing a bridge loaded by this type of vehicle would be the position of the vehicle on the bridge (transverse and longitudinal) and its weight. While a variety of techniques are available to answer the position question, the load is far more difficult to assess without intruding on the roadway surface (Bushman and Pratt, 1998). Instead, this study engages in a novel social experiment that uses education and incentivization programs to motivate commercial truckers to self-report their payloads. While securing and sustaining their participation is a separate aspect of the study that deals with issues of the technology adoption life cycle as well as social science and policy research, their required actions to support the technical aspects of this project are simply as follows: participating truckers would be provided a secured user account and identification number tied to a small, inexpensive, passive RFID tag that can be affixed to their cab without requirements for power. They would then be asked to self-report their payload (gross or per axle loads) at the time of pickup and delivery by telephone or internet. This information is logged in a central database. When the truck arrives at one of the instrumented bridges, a gateway station up traffic of the bridge scans the tag and retrieves the most up-to-date payload information via cell phone-enabled internet from the central database. Following a quality control check, if the loading conditions match the target scenario (e.g., specified weight range and environmental condition quantified by a meteorological station), the sensor network is activated. These two actions are respectively depicted as the Citizen Self-Reporting Stage and the Input Selection Stage in Figure 2. At minimum, the RFID scanning technology delivered to enable this form of selection and activation must be capable of reading tags passing at upwards of 70 mph in traffic. To do so, RP Global Technologies, a partner in this effort, is developing long distance RFID tags readable over 100 feet, making it possible to use the tags to measure the location of a vehicle passing over the instrumented bridge.

**Other Venues for Citizen-Centric Assessment**

While this project represents two levels of possible citizen engagement in infrastructure assessment, they are but a small portion of a larger ongoing effort being led by the University of Notre Dame to explore Open-Sourcing the Design of Civil Infrastructure. This four year Cyber-Enabled Discovery and Innovation Project funded by the National Science Foundation is currently developing various prototypes for crowd sourced engineering tasks. In the summer of 2010, this effort will include citizen engineers being tasked with the collection of visual evidence of infrastructure degradation using smart phones that automatically upload captured images and GPS coordinates to a web-based repository, where other members of the citizen engineering crowd can evaluate the level of damage suspected in these images. By mobilizing citizens at large to collect images of troubled infrastructure, the capability for alerting of potential troubled structures in the period between their regular inspections is greatly enhanced. As such, the public at large represents a considerably untapped resource as intelligent sensors themselves, capable of collecting and transmitting massive amounts of data than can be effectively mined by trained engineers. Further, by these simple engagements of the general public, overall attitudes and awareness surrounding civil infrastructure will be heightened. This represents again an opportunity for citizens to participate actively in the assessment process of the bridges they use every day, making them stewards of our national infrastructure and allies with the civil engineering community in reversing our infrastructure crisis.
Conclusions

Sadly the current state-of-the-art in bridge monitoring has erected a technology adoption barrier that has effectively isolated the end users of technology (transportation officials) from the technologies themselves. To transportation officials, SHM may be an abstract concept engineered in a research laboratory with no real tangible benefit to them. The technologies are expensive, foreign and not cognizant of the fiscal constraints and needs of the community. Thus widespread adoption of structural health assessment using embedded sensor networks has not been realized, as end users have not been given the opportunity to become advocates for the technology by employing it themselves. And while every researcher is quick to acknowledge that there remain questions to be answered to enhance the performance and reliability of every proposed system, these systems continue to be designed for deployment, operation and interrogation by technicians and researchers and not the end users themselves. In response to this need, this study introduces a concept called CITI-SENSE: a citizen-centric health monitoring paradigm that, through its innovations in hardware and networking, delivers flexible sensing technologies directly to citizen end users and even enlists the participation of commuting citizens in the assessment process. Certainly there is substantial technical challenge involved in the development of a sensing paradigm that has sufficient flexibility to be deployed and operated at will by citizens with no background in electronics or signal processing, but the ability to achieve this would be transformative, eliminating the barriers that have precluded widespread use of SHM for infrastructure assessment and decision making. This therefore represents a truly citizen-centric health monitoring philosophy that can replace the current subjective, infrequent and inaccurate visual inspection paradigm. Ultimately, when couched in an appropriate risk assessment framework, this approach can enable the ultimate outcome: pro-active maintenance of civil infrastructure, enhancing public safety while minimizing costs to taxpayers and intrusion to commuters. However, these outcomes are only enabled by finally removing technological barriers to deliver the latest assessment technologies to the people and enlisting them as active participants in the assessment of the infrastructure they rely on. This paper represents the first step in launching this new effort.

Acknowledgements

The authors wish to acknowledge the seed funding provided by their individual institutions/companies as well as their collaboration with Robert Palevich of RP Global Technologies. Additional crowd-sourced assessment efforts are affiliated with NSF Grant CBET-09-41565 and collaborators David Hachen, Ahsan Kareem, Gregory Madey and Douglas Thain of the University of Notre Dame.

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